Impact of drainage and soil properties on carbon dioxide emissions from intact cores of cultivated peat soils

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SUMMARY

Drained peatlands contribute to anthropic emissions of carbon dioxide (CO_2), so a better understanding of the underlying processes and identification of mitigation options for agricultural peatlands are urgently required. Peatland soil properties vary greatly and, in combination with drainage, can affect emissions of CO_2 both directly and indirectly. Drainage reduces soil water content but increases CO_2 production, so it is important to find the optimum drainage level that minimises CO_2 emissions without affecting agricultural use. Intact soil cores from nine different sites (topsoil, plus subsoil at four sites) were collected and brought into a controlled laboratory environment. Repeated measurements of CO_2 fluxes were performed at increasing soil water suctions corresponding to different drainage levels. Physical and chemical properties of the soils were determined and compared with the CO_2 emissions. The soil cores displayed different CO_2 emission patterns with increasing soil water suction head. In some cores, emissions increased rapidly to a high level, while in others they remained at lower levels. At a soil water suction head of only 0.5 m of water, the average soil CO_2 emissions had already reached a maximum. The soil cores represented peat soils with a wide range of soil properties, *e.g.* bulk density from 0.17 to 0.47 g cm^{-3} and total carbon from 26.3 to 43.5 %, but none of the properties measured was clearly correlated with CO_2 emissions.

KEY WORDS: CO_2, laboratory suction apparatus, peaty marl, subsoil, suction head, topsoil

INTRODUCTION

Global carbon dioxide (CO_2) emissions from drained peatlands increased by about 20 % between 1990 and 2008. After Indonesia, the European Union (EU) is the world's second largest emitter of CO_2 from drained peatlands (Joosten 2009). In Sweden, drained peatlands used for agriculture represent 7 % of all agricultural land and contribute 6–8 % of the country's total anthropic emissions of CO_2 and nitrous oxide (N_2O) (Berglund & Berglund 2010, Pahkakangas *et al.* 2016). Drained agricultural peatlands can subside at rates of 0.5–2.5 cm *per* year, depending on soil type, reflecting a loss of agricultural soil (Berglund 1989). Thus, there is a need to reduce both CO_2 emissions and peat subsidence rates, for climate and farm economic reasons, respectively (Kløve *et al.* 2017). Knowledge of the processes that lead to CO_2 production in peat and how they differ between peat soil types is essential to the search for options to reduce CO_2 emissions.

Temperature and water content (air-filled pore space) are the most important factors controlling CO_2 production in agricultural soil (Mäkiranta *et al.* 2009, Berglund & Berglund 2011, Renou-Wilson *et al.* 2014). Factors such as substrate availability (Carrera *et al.* 2015), amendments (e.g. lime) (Susilawati *et al.* 2016) and land management (Haddaway *et al.* 2014) can also influence CO_2 emissions from drained agricultural peat soils, with drainage intensity reported to be the most important factor connected to management (Beyer *et al.* 2015). However, the question of an optimal drainage depth to reduce greenhouse gas emissions without affecting agricultural production is now being intensively discussed and it has been suggested that a drainage depth of 30 cm is optimal in this regard (Renger *et al.* 2002, Regina *et al.* 2015). It has also been reported that CO_2 emissions are doubled by lowering the groundwater level from 30 to 80 cm below the ground surface (Renger *et al.* 2002). However, in a study by Berglund & Berglund (2011) comparing water table depths of 40 and 80 cm, the opposite effect was found. Rewetting of agricultural peatlands is being discussed as a means of reducing emissions (e.g. Hjerpe *et al.* 2014, Schrier-Uijl *et al.* 2014, Knox *et al.* 2015) but this can lead to other problems such as nutrient leaching (Harpenslager *et al.* 2015) and may not be a viable option in all cases.

Studies by Norberg *et al.* (2016a, 2016b) found that greenhouse gas emissions varied between sites (*i.e.* soils), which indicates that soil properties are a regulating factor. Histosols (peat soils) have at least

12–18 % organic carbon by weight, but usually much more (Soil Survey Staff 2014). This means that peat soils can be very diverse in their organic matter content, and contradictory responses of CO_2 emissions to drainage of different peat types have been reported in the literature (Renger *et al*. 2002, Regina *et al*. 2015). Dissolved organic carbon (DOC) is closely linked to microbial activity and C mineralisation in soil (Chow *et al*. 2006, Bowen *et al*. 2009) and could, therefore, be a good indicator of CO_2 emissions. In addition, pH, nitrate (NO_3) content and peat decomposition have been shown to affect soil respiration (Scanlon & Moore 2000, Szafranek-Nakonieczna & Stepniewska 2014). However, in a study of arctic tundra peat soils of varying quality and carbon content, Biasi *et al*. (2014) found soil respiration to be similar at all sites and none of the soil factors tested was correlated with CO_2 production. Eickenscheidt *et al*. (2015) found that the type of agricultural land use was more important than soil organic carbon content for CO_2 emissions from peat soils. On the other hand, Danevčič *et al*. (2010) identified groundwater level as more important than soil organic carbon content and surface cover in controlling CO_2 emissions from a drained fen.

The aim of the present study was to determine whether any particular soil property influences the CO_2 emissions in agricultural peat soils and how drainage (aeration) influences CO_2 emissions from different peat soils. This was done by measuring, in a controlled laboratory environment, the rate of CO_2 emissions from intact soil cores (13 different soils) subjected to different soil water suction heads from 0.05 m (near water-saturated) to 1.0 m water column. Increased suction head leads to decreased soil water content and increased air-filled pore space (Berglund & Berglund 2011). The different soil water suction heads correspond to groundwater depths in field conditions down to 1 m below the soil surface. Soil physical and chemical analyses were carried out on the same soil cores. Since the work was performed in controlled conditions on intact soil cores, it was possible to evaluate the impact of increasing suction head and of soil properties without the disturbing factors, such as weather and vegetation, that complicate field studies. The drainage equilibrium established in the laboratory is seldom found in the field, where topsoil water content normally varies despite a stable groundwater level. The hypotheses tested were that: i) peat soils respond differently in terms of CO_2 emissions to increasing soil water suction, due to differences in soil properties; and ii) one or several soil properties can explain the CO_2 emissions in peat soils.

METHODS

Topsoil samples were collected in autumn 2011 at nine different agricultural sites located in southern Sweden (Table 1). At four of the sites (Sites 6–9), subsoil samples were also collected from the same locations, giving a total of 13 different soils. All the sites had peat soils with the exception of Site 4, where the soil type was peaty marl. All were active farms with the exception of Site 9, which was once a dairy farm but had been abandoned for several years. Site and soil descriptions are provided in Table 1 and some soil properties are presented in Table 2.

Soil sampling

Prior to soil sampling, the surface vegetation was removed. Intact soil cores were sampled in steel cylinders (7.2 cm diameter, 10 cm high) at approximately 5–15 cm depth for topsoil samples and 20–50 cm depth for subsoil samples. Ten replicates, plus a few extra for precaution, were taken within a small area (< 1 m^2) from each soil. Upon extraction, the cylinders were sealed at both ends with plastic lids and stored in wooden boxes. The boxes were transported directly from the field to a cold store (5 °C) where they were kept until the experiment started.

Drainage and CO_2 emissions experiment

At the start of the experiment, the soil samples were distributed into seven separate boxes. Each box contained one sample of each of the 13 soils; with a total of 91 samples distributed between the seven boxes. All boxes were treated similarly and were assumed to be independent in the statistical analysis. The boxes were brought from the cold store into the experiment one at a time. Before the start of measurements, the relevant box was kept at laboratory temperature (maintained at 20 °C) for two days and then the 13 soil cylinders were soaked in tap water for three days until saturated. During these initial days, the samples were carefully observed and replaced if necessary, *e.g*. if they were disturbed by any earthworms in the soil. The 13 samples were then placed on a suction sand bed (Romano *et al*. 2002) for successive adjustment to soil water suction heads of 0.5 m and 1.0 m water column (approximately 5 and 10 kPa) (Figure 1). In addition, three of the soil sample boxes were adjusted to a suction head of 0.75 m water column, and one of these boxes was subjected to an additional suction step of 0.25 m water column (Table 3). At each suction step, it took about seven days to reach equilibrium (when drainage of water was observed to have ceased).

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Table 1. Descriptions of the soils and farm types at the sampling sites in Sweden. Topsoil samples only were taken at five sites (Soils 1–5), and topsoil plus subsoil samples were taken at four sites (Soils 6–9). Subsoil samples are marked "sub".

Soil no.	Sample depth	Soil description	Type of farm	Coordinates
1	5–15 cm	Fen peat	Dairy farm growing grass and cereals for feed	59° 18 'N 16° 32 'E
2	5–15 cm	Fen peat	Farm growing cereals and vegetables (carrot, potato)	59° 11' N 15° 35' E
3	5–15 cm	Fen peat with lime	Dairy farm growing grass and cereals for feed, plus vegetables	57° 34' N 18° 38' E
4	5–15 cm	Peaty marl	Farm growing cereals and vegetables (carrot, potato)	57° 44' N 18° 27' E
5	5–15 cm	Fen peat with lime gyttja subsoil	Farm growing cereals and vegetables (carrot, potato)	57° 42' N 18° 29' E
6 6_{sub}	5–15 cm 40–50 cm	Fen peat with stones Fen peat (*Phragmites*) with gyttja intrusion	Dairy farm growing grass and cereals for feed	58° 07' N 13° 32' E
7 7_{sub}	5–15 cm 20–30 cm	Fen peat with clay intrusion Fen peat (*Phragmites*)	Dairy farm growing grass and cereals for feed	58° 07' N 13° 32' E
8 8_{sub}	5–15 cm 20–30 cm	Fen peat Fen peat (*Phragmites*)	Dairy farm growing grass and cereals for feed	58° 07' N 13° 32' E
9 9_{sub}	5–15 cm 30–40 cm	Fen peat Fen peat	Old dairy farm, now an abandoned field	60° 01' N 17° 26' E

Table 2. Humification degree, pH, total carbon content (Tot-C) and carbon/nitrogen quotient (C/N) of the 13 topsoil and subsoil samples taken at nine sampling sites in Sweden.

Soil no.	Humification degree (von Post)	pH (H_2O)	Tot-C (%)	C/N
1	H9–10	5.2	26.7	16
2	H9–10	5.2	42.7	21
3	H9–10	7.6	31.6	14
4	(peaty marl)	8.0	9.7	11
5	H10	7.5	35.8	14
6	H10	6.1	37.1	11
6_{sub}	H5–6	6.1	43.5	15
7	H9–10	7.5	26.3	11
7_{sub}	H3–4	7.6	27.4	16
8	H9–10	5.0	37.3	12
8_{sub}	H3–4	5.2	42.2	16
9	H9–10	5.4	39.0	14
9_{sub}	H8–9	5.4	39.2	16

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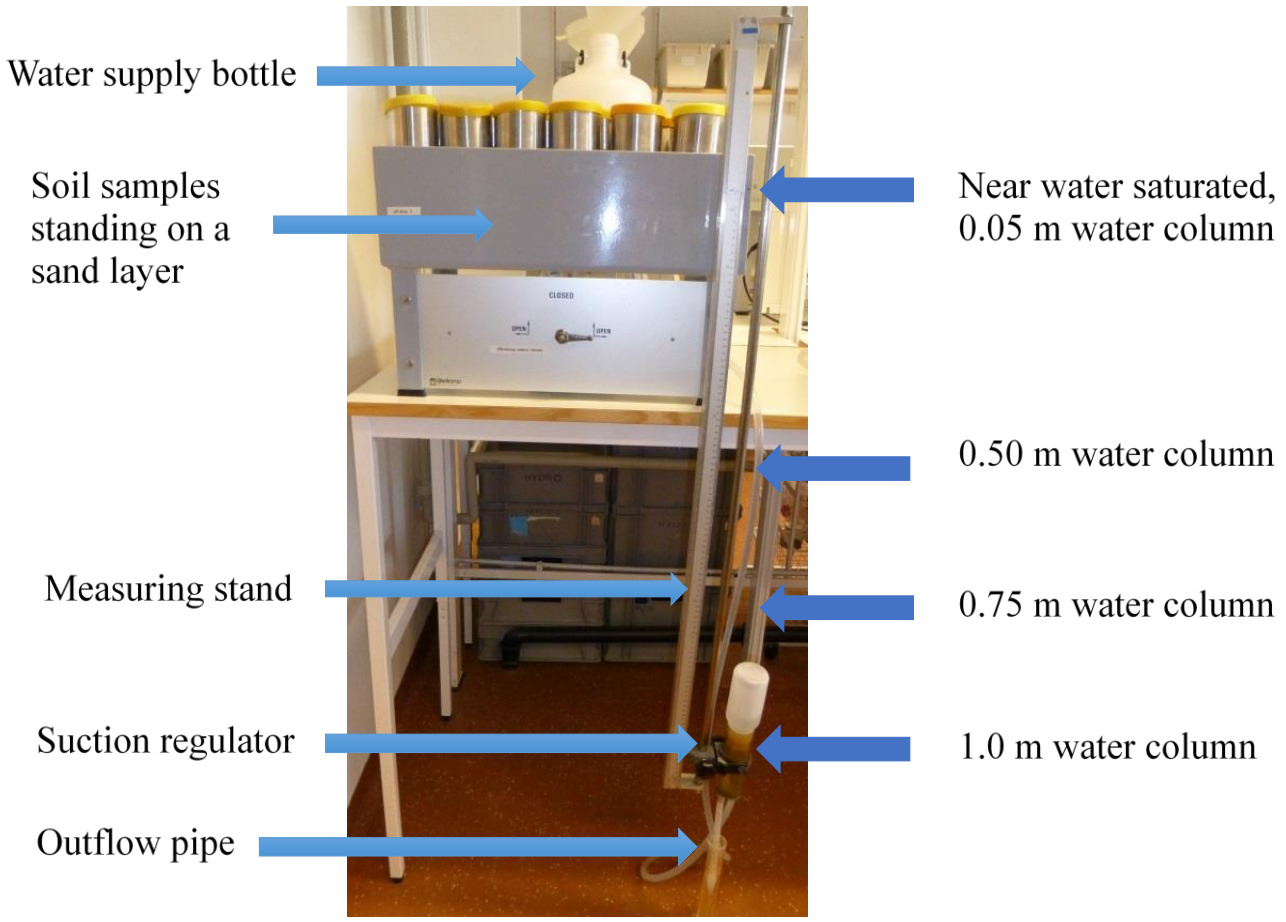

Figure 1. The sand bed that was used to apply suction to the soil samples. The difference in height between the suction regulator and mid-depth in the soil samples determines the amount of suction. Suction heads between 0 m and 1.0 m can be applied. Examples of suction heads used in this study are shown on the right-hand side of the picture.

Table 3. Schematic description of the experimental design with six different soil water suction heads, seven boxes and two after-uses of the samples. The boxes that were subjected to CO_2 measurements at each soil water suction head are marked 'x'. Each box contained one sample from each of the 13 soils. The after-use of the samples in each box was for either soil analyses (sa) or dry weight (dw) calculations.

	soil water suction head (m water column)					after-use
	0.05	0.25	0.5	0.75	1.0	
Box 1	x		x		x	sa
Box 2	x		x		x	sa
Box 3	x		x		x	sa
Box 4	x		x		x	dw
Box 5	x		x	x	x	dw
Box 6	x		x	x	x	dw
Box 7	x	x	x	x	x	dw

Prior to CO_2 emission measurements, the soil samples were weighed for water content. When all of the CO_2 emission measurements were complete, each of the soil cores in three of the boxes was divided into two sub-samples; one for the freezer (-18 °C) and one for the refrigerator (5 °C). These samples were then used for different soil analyses. The soil cores from the four remaining boxes were dried for 72 h at 105 °C and weighed for dry-weight-based emissions calculations. The mean dry weight of the four replicate soil samples in the second set of boxes was taken as the dry weight of each of the three corresponding soil samples in the first set of boxes.

CO_2 emission measurements

For the CO_2 emissions measurements, we used polypropylene jars of suitable size for a soil sample cylinder to fit inside (11 cm diameter, 12 cm high, volume 1140 cm^3). Each jar had an airtight screw lid equipped with two injection needles (0.8 mm diameter, 40 mm long). The needles were inserted through the lid and glue was applied around the insertion points to ensure the that the modified jar was airtight. The jars had thick walls (approximately 1.5 mm) and potential leakage of gas was considered to be negligible. The CO_2 emissions from the different soils were determined by placing a soil sample cylinder in a jar, immediately closing the lid, and then connecting the injection needles *via* plastic tubing to a portable infrared CO_2 analyser (Carbocap CO_2 Probe GMP343, Vaisala Ltd, Vantaa, Finland). Measurements were made every 30 s for 5–10 minutes. Within this range, longer jar closure times were used at lower emission rates. The CO_2 analyser was calibrated before the experiment started, according to the manufacturer's standard procedures (Vaisala Instruments Service, Vantaa, Finland).

Gas measurements were performed on one sample at a time until all of the samples (1–13) in the tray had been measured. The measuring procedure was performed twice on all samples at each measuring occasion (suction step). The jar and the gas analyser were allowed to ventilate between samples. The rate of CO_2 emission from the soil was calculated from the linear increase in CO_2 concentration in the jar headspace during the closure time. In general, emission fluxes with linearity higher than $r^2 = 0.85$ were used, but measurements with lower r^2 were included if they did not exhibit any obvious errors on visual inspection. Negative values were omitted. Most of the omitted values (35 out of 51) were obtained near water-saturation. Mean values of the two measurements *per* occasion were used in the statistical analysis except in cases where values were missing, when only one value was used.

The CO_2 emission flux was calculated using Equation 1 (described in Kainiemi *et al*. 2015):

$$F = \Delta CO_2 \times \frac{PVM}{RT} \quad [1]$$

where F is the CO_2 flux (mg min^{-1}), ΔCO_2 is the increase in CO_2 concentration in the jar during closure (ppm CO_2 min^{-1}), P is atmospheric pressure (101,325 Pa), V is the volume of air in the jar (L), M is the molecular mass of CO_2 (44 g mol^{-1}), R is the gas constant (8.3145 J mol^{-1} K^{-1}) and T is the ambient temperature (293 K). Air volume (V) was calculated by subtracting the volume of the cylinder from the internal volume of the jar. The CO_2 flux values were then divided by the dry mass of the soil sample to express *per* unit mass of dry soil (mg g^{-1} min^{-1})

Soil analysis

Three soil cylinders (not used for CO_2 measurements) from each soil were used for analysis of soil physical properties. Dry bulk density and volumetric water content at suction heads of 0.05, 0.25, 0.5, 0.75 and 1.0 m water column (approximately 0.5, 2.5, 5.0, 7.5, and 10.0 kPa) were determined. Air-filled pore space at different suction heads was calculated from water retention data. Humification degree (H1–H10) of the peat soils was determined according to von Post (1922).

The frozen soil samples from the drainage experiment were used for analysis of mineral N (nitrate (NO_3) and ammonium (NH_4)) on a TRAACS 800 AutoAnalyzer (Bran&Luebbe, Germany). The soil stored in the refrigerator was used for different analyses soon after completion of the gas measurements. Total nitrogen (tot-N), total carbon (tot-C) and carbonate carbon (carb-C) content were determined by dry combustion on a LECO CN-2000 analyser (St. Joseph, MI, USA). Soil pH was measured at a soil:solution ratio of 1:5 with deionised water. Organic matter content (loss on ignition) was measured by dry combustion at 550 °C for 24 h after pre-drying at 105 °C for 24 h.

Water-extractable organic carbon (WEOC), presented here as total and filtered WEOC ($WEOC_{tot}$ and $WEOC_{fil}$, respectively) was determined by a modified version of the method of Ghani *et al*. (2003). Approximately 3.5 g of soil was placed in a 50 mL polypropylene centrifuge tube, made up to a 1:5 soil:water suspension with deionised water, and placed on an end-over-end shaker for 1 h. The tube was then centrifuged at 3500 rpm for 20 minutes. The supernatant was decanted into a new tube and analysed for $WEOC_{tot}$ on a Shimadzu TOC-5000A. The supernatant was then filtered through a 0.45 µm

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membrane filter and analysed again for $WEOC_{fil}$. In parallel, a similar quantity of soil was dried at 105 °C for 24 h (for dry weight determination). The analytical data were then recalculated using the dry weight data and the results were presented as mg $WEOC_{tot}$ or $WEOC_{fil}$ *per* g total C in the soil.

Statistical analysis

One-way ANOVA was used to test for differences in CO_2 emissions caused by suction head increments, soils and boxes. For the ANOVA, the data were square root-transformed to meet the requirements of normality and equal variances. Relationships between CO_2 emissions and soil properties were tested with linear and non-linear regression. Pair-wise comparisons of soils, soil properties and CO_2 emissions at different suction heads and between topsoils and subsoils were performed with T-test and Tukey's adjustment. All statistical analyses were carried out in Minitab 17 (Minitab. Inc. USA). Mean values ± standard deviation (SD) are presented.

RESULTS

CO_2 emissions and drainage

The mean CO_2 emission rates (± SD) for all 13 soils (dry mass basis) were 36 ± 40, 142 ± 84, 166 ± 70 and 167 ± 77 mg g^{-1} min^{-1} at suction heads near saturation (0.05), 0.5, 0.75 and 1.0 m water column, respectively. There were no significant differences in CO_2 emission rates between suction heads of 0.5, 0.75 and 1.0 m water column, but the emission rate near saturation deviated significantly from the others ($p < 0.05$).

The response of CO_2 emission rate to increased suction (decreased soil water content), expressed *per* unit mass of dry soil, varied between the soils. For some soils it increased slowly with increasing suction head, while for others it stayed at the same level when the suction head increased from 0.5 to 1.0 m water column (Figure 2). Mean CO_2 emission rates from topsoil and subsoil at the same site were higher for the topsoil at three out of four sites for which this comparison could be made (Sites 6–9) (Figure 2). The peaty marl soil (Soil 4) had the lowest CO_2 emission rate at all suction steps. At a suction head of 1.0 m water column, CO_2 emission rates for the peat soils (excluding Soil 4) ranged from approximately 100 to 250 mg g^{-1} min^{-1} (Figure 2). At this suction head, none of the eight peat topsoils deviated significantly from all the other soils (Figure 3), although Soils 1 and 7 (low emission rates) deviated from Soils 3, 5, 6 and 8 (high emissions) ($p < 0.05$).

The air-filled pore space (AFPS) increased with increasing suction head (Figure 4). The highest AFPS

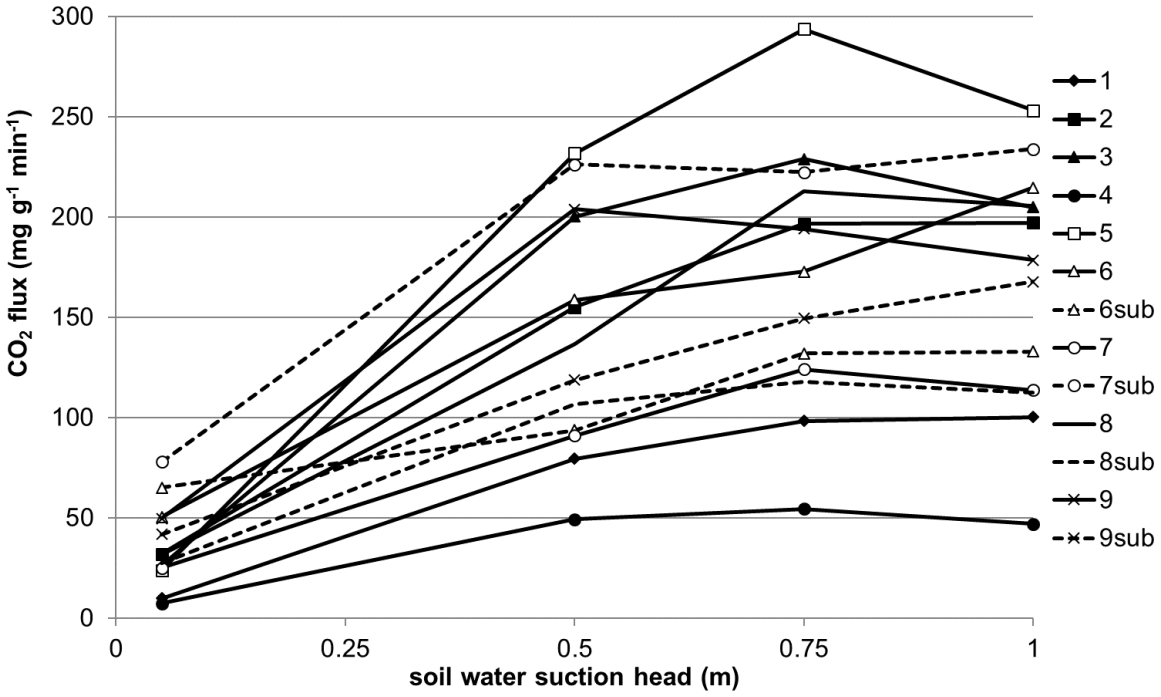

Figure 2. Carbon dioxide emission rates (mg g^{-1} min^{-1}; dry mass basis) from the 13 soils at suction heads of 0.05 (near water-saturated), 0.5, 0.75 and 1.0 m water column. Data for topsoils are indicated by solid lines and those for subsoils (Sites 6–9 only) by dashed lines. For 0.75 m suction head, $n = 3$; for all other suction heads, $n = 7$.

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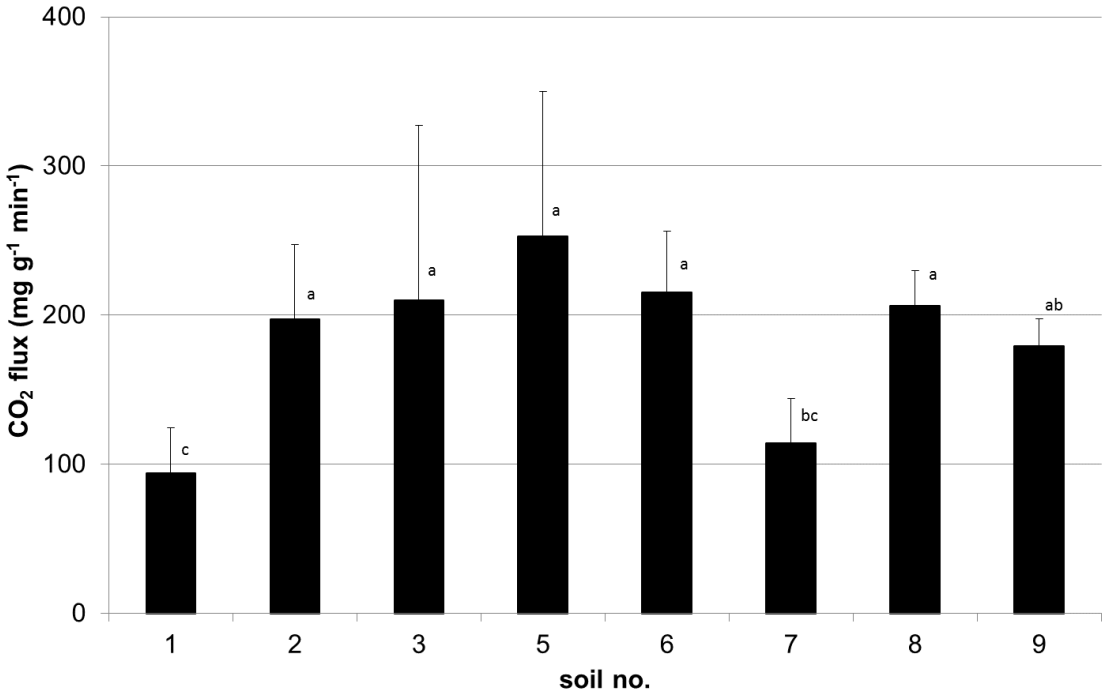

Figure 3. Carbon dioxide emission rates (mg g^{-1} min^{-1}, dry mass basis) from the eight peat topsoils (Sites 1–3 and 5–9) at a suction head of 1.0 m water column ($n = 7$). Different letters in the labels denote significantly different values ($p < 0.05$).

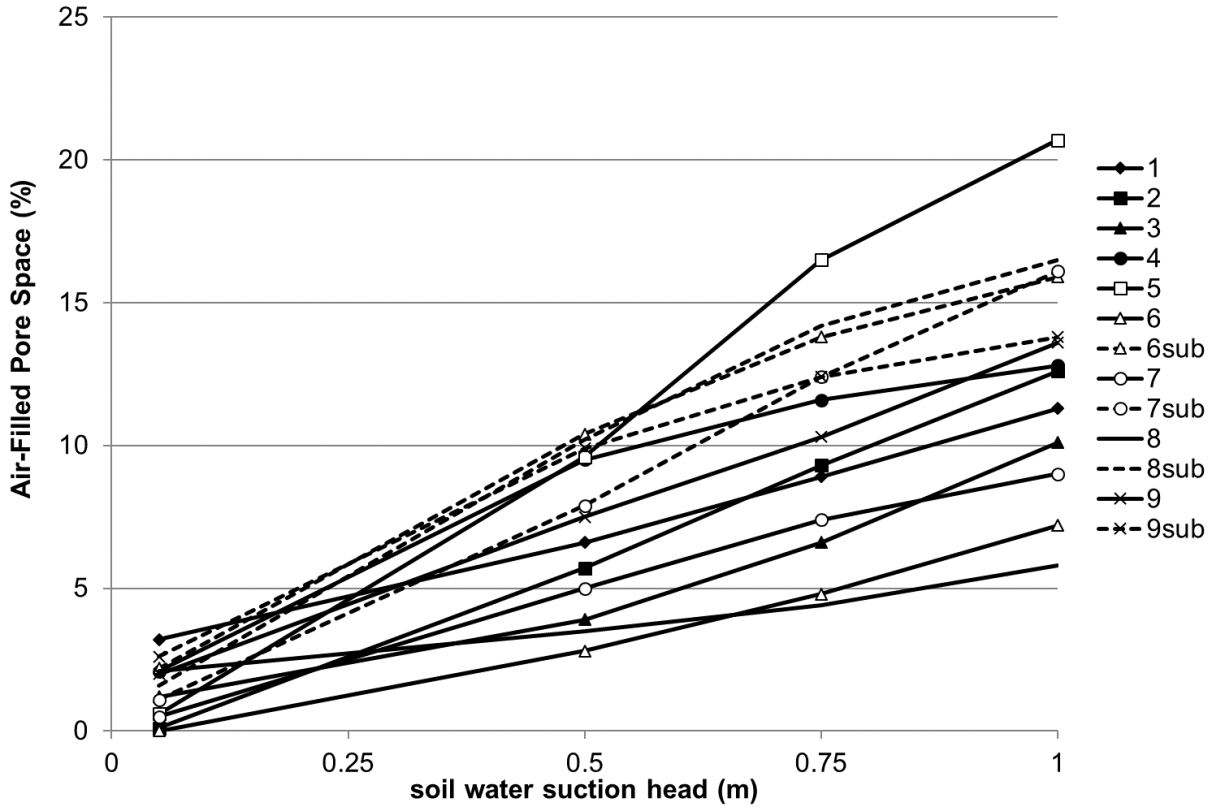

Figure 4. Air-filled pore space (%) for the 13 soils at suction heads of 0.05 (near water-saturated), 0.5, 0.75 and 1.0 m water column ($n = 3$). Data for topsoils are indicated by solid lines and those for subsoils (Sites 6–9 only) by dashed lines.

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value recorded at a suction head of 1.0 m water column was 21 % (Soil 5), while the lowest was 6 % (Soil 8). At suction heads of 0.5, 0.75 and 1.0 m water column, AFPS was generally higher in subsoils than in topsoils, which indicates a difference in soil structure (pore size distribution) between topsoil and subsoil. There was no relationship between AFPS and CO_2 emission rate.

For the 13 soil samples in Box 7, whose CO_2 emission rates were measured at five different suction head steps (see Table 1), CO_2 emissions increased rapidly from near water-saturated conditions to their maximum levels at 0.5 m water column, and stayed at these maximum levels at subsequent suction steps (data not shown).

CO_2 emissions and soil properties

The relationship between CO_2 emission rates and soil properties was examined for a suction head of 1.0 m only (because the soil analyses were mainly carried out at the end of the experiment) and without the peaty marl soil (Soil 4, tot-C content 10 %) which deviated strongly from the peat soils (tot-C 26–44 %). The soils exhibited a wide range of organic carbon content, but a statistical relationship with CO_2 emissions was not observed (Figure 5a). Four soils (3, 5, 7 and 7_{sub}) had high carbonate-C content (Figure 5b) due to the presence of calcareous minerals. One of the subsoil samples (Soil 9_{sub}) deviated strongly from the other soils in $WEOC_{fil}$ content, but no general relationship with CO_2 emissions could be found (Figure 5c). Loss on ignition showed no statistical relationship with CO_2 emissions (Figure 5d) and there was no difference between topsoils and subsoils. Soils 9 and 9_{sub} had much higher NO_3 content than the other soils (Figure 5e). Soil 7 had a very high NH_4 content and when that value was omitted there was a linear relationship ($p < 0.05$) between CO_2 emissions and NH_4 content (Figure 5f). Topsoil generally had higher bulk density than subsoil, reflecting the higher humification degree in the topsoil (Figure 5g and Table 2). Two of the soils (1 and 7) deviated from a possible linear relationship between CO_2 emission rate and bulk density (Figure 5g) and had significantly lower CO_2 emission rates than several of the other topsoils (Figure 3). They deviated from the other topsoils by having lower tot-C content, lower organic carbon content and lower $WEOC_{fil}$ while for NH_4 they were at opposite ends of the scale (Table 2, Figure 5). However, they showed no differences from the other soils in terms of pH and NO_3.

DISCUSSION

CO_2 emissions and drainage

In this laboratory experiment, performed under controlled conditions using intact soil cores, the CO_2 emission patterns of peat soils exhibited a wide range of responses to increasing drainage (suction head) (Figure 2). The different suction steps applied to the topsoil samples (0.5, 0.75 and 1.0 m water column) corresponded to water table depths in field conditions of 50, 75 and 100 cm below the soil surface. However, drainage equilibrium occurs in the field only during short periods, *e.g*. early in spring after a wet winter, when the soil frost has gone and evapotranspiration is negligible. Water content in the topsoil is often much lower than the groundwater level indicates, due to evapotranspiration and slow capillary transport from below. The CO_2 emission curves in Figure 2 show a wide range of responses to increasing suction head for the 13 different soils tested. Some soils responded with an instantaneous large increase in CO_2 emission rate, while in other soils the CO_2 emission rate increased only moderately or remained low. This confirms the hypothesis that different peat soils respond to drainage in different ways. This was also seen in a study by Tiemeyer *et al*. (2016), where the response of CO_2 emissions to groundwater level was highly site-specific. Mäkiranta *et al*. (2009) reported that the relationship between groundwater level in the field and peat decomposition rate followed a bell-shaped curve, with an optimum groundwater level approximately 60 cm below the surface. In the present study, some of the CO_2 emission curves showed tendencies towards a bell shape but, on average for all soils, there was no difference between suction heads of 0.5, 0.75 and 1.0 m water column.

For the box subjected to an additional suction step of 0.25 m water column, a linear increase was seen in CO_2 emissions from near water-saturated conditions to a suction head of 0.5 m water column, as reported previously by Moore & Dalva (1993) and Susilawati *et al*. (2016). Moore & Dalva (1993) observed a 4.3-fold increase in CO_2 emissions between water-saturated conditions and drainage to 40 cm depth, compared with the 3.9-fold increase between near water-saturated and a suction head of 0.5 m water column observed in the present study. In our study, the CO_2 emission rate from Soil 9 peaked at a suction head of 0.5 m water column and that from Soil 7 at a suction head of 0.75 m water column, then slowed down. In an earlier incubation experiment (Berglund & Berglund 2011) these same two soil types showed

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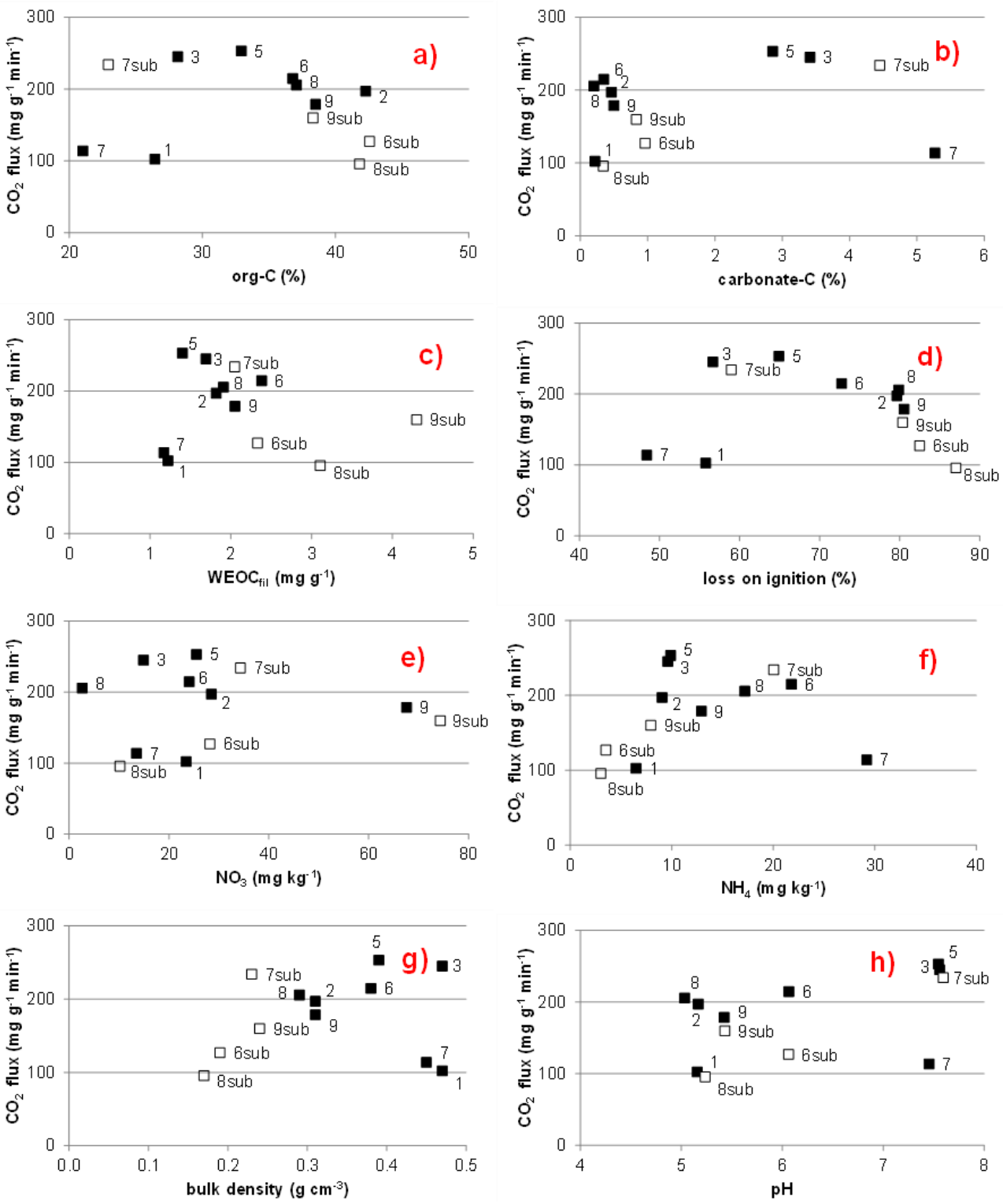

Figure 5. Relationships between carbon dioxide emissions (mg g^{-1} min^{-1}, dry mass basis) at a suction head of 1.0 m water column and selected soil factors: a) organic carbon (org-C); b) carbonate carbon (carbonate-C); c) water-extractable organic carbon ($WEOC_{fil}$); d) loss on ignition; e) nitrate (NO_3); f) ammonium (NH_4); g) bulk density; and h) pH. Soil 4 (peaty marl) is not included. Data for topsoils are indicated by filled squares and data for subsoils by open squares.

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similar bell-shaped behaviour and CO_2 emissions slowed down considerably at a suction head of 6 m water column.

In this study, mean CO_2 emission rates (dry mass basis) at near water-saturated conditions ranged from 7 to 78 mg g^{-1} min^{-1} (Figure 2). This wide range of relatively high emissions could be due to the presence of oxygen in the water used for saturation, the presence of trapped air (and CO_2) in micropores, and some drainage of water that occurred when the soil samples were moved and placed in the measuring jars. The CO_2 emissions under near water-saturated conditions might have been lower if the water had been boiled before use (to remove air bubbles) and with a slower and more prolonged saturation time. Another reason for this wide range in CO_2 emissions could be that several measurements that were omitted should perhaps have been treated as zero emissions, thus giving lower mean values.

According to Renger *et al*. (2002) the lifespan of a drained fen peat can be extended from 130 years to more than 500 years by raising the groundwater level from 70 cm to 30 cm below the ground surface and thus preventing subsidence This would be of great economic importance for farmers. However, yield and trafficability also need to be considered when managing groundwater levels in agricultural systems. Poyda *et al*. (2016) demonstrated the potential for reducing greenhouse gas emissions from agricultural areas in northern Germany without giving up traditional forage production, by changing land use intensity and groundwater level. Moreover, Renou-Wilson *et al*. (2016) reported lower CO_2 emissions from extensively grazed unfertilised fields than from other agricultural areas on peat because of higher annual mean groundwater levels (above -25 cm). Also, different plant species can respond in different ways to higher groundwater levels. For example, field and mesocosm experiments have demonstrated that pasture plants (used for grazing) and reed canary grass (used for energy biomass) are suitable for production on organic soils with shallow groundwater levels (Karki *et al*. 2014, Campbell *et al*. 2015).

In practice, it is difficult to keep the water table at a specific level. Furthermore, both groundwater levels and CO_2 emissions vary greatly between years in the field (Danevčič *et al*. 2010, Poyda *et al*. 2016), and Regina *et al*. (2015) found that CO_2 flux rates also vary when the groundwater level is stable. Very low hydraulic conductivity and slow capillary rise are common in many peat soils (*e.g*. Mustamo *et al*. 2016), which means that water content in the topsoil during the growing season is determined more by weather and uptake of water by plants than by groundwater level. The outcome is variable CO_2 emissions and a weak relationship between groundwater level and CO_2 emissions in the field (Tiemeyer *et al*. 2016). Soil moisture or aeration could be a better predictor for CO_2 emissions than groundwater level under field conditions, since water table depth does not determine the soil moisture content in the upper layers of soil (Price 1997). It is worth noting that, in this laboratory study, the topsoil moisture content never reached such low levels as are commonly found in the field (Norberg *et al*. 2016a).

Temperature is important for CO_2 production. In this laboratory study, the temperature was kept constant at 20 °C, which is much warmer than the average field temperature during the growing season in Sweden. Soils 7 and 9 were used in a previous study, where a rise in temperature from 13 °C to 25 °C in an incubation experiment increased CO_2 emissions 4.2-fold and 2.6-fold, respectively (Berglund *et al*. 2010). In a related lysimeter experiment, the average Q_{10} value for both soils was 2.1 for temperatures between 13 °C and 25 °C. In a study by Moore & Dalva (1993), a rise in temperature from 10 °C to 23 °C increased CO_2 emissions 2.4-fold. The constant temperature in the laboratory could also be a reason for the shape of the average CO_2 emissions curve. The high temperature may permit soil microbes to operate at constantly high levels of activity, especially as the soil water content in the samples was relatively high even at a suction head of 1.0 m water column. Another reason for the shape of the average CO_2 emissions curve observed here could be changes in microbial populations, whose composition might have altered during the experiment due to the long period of warm temperature and possibly a change in substrate availability (Moore & Dalva 1993). Since the samples were intact, they still contained roots and other easily degradable carbohydrates and the availability of this substrate may have changed over the experimental period of several weeks. This could be a reason why CO_2 emissions did not increase at suction heads higher than 0.5 m water column. If the substrate availability had been constant, a greater suction head (more aeration/deeper drainage) would perhaps have led to higher emissions.

CO_2 emissions: subsoil *versus* topsoil

With all soils included, there was no apparent difference between subsoil and topsoil samples in the magnitude of CO_2 emissions and the shapes of CO_2 emission curves, except that the subsoils appeared to have higher CO_2 emissions under near water-saturated conditions (Figure 2). This may be related to the fact that the microbes in the subsoil were better

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adapted to anoxic conditions than those in the topsoil, which is more aerated. It is important to remember that under field conditions a groundwater level of 1.0 m below the soil surface, for example, results in a different soil water suction head for every sublayer depth in the soil profile, so subsoil and topsoil do not experience the same soil water suction head at the same time. Thus, the laboratory study is not totally realistic.

A similar trend to our observation of higher CO_2 emissions from topsoil than from subsoil was reported by Glatzel *et al*. (2004), while Harpenslager *et al*. (2015) did not find any difference. Newly deposited fresh organic matter (roots and plant litter) from agricultural crops generates the potential for higher CO_2 production in topsoils. Furthermore, the humification degree decreased with depth in the soil profile at all of our study sites (Table 2).

For the four sites with subsoil and topsoil samples available (Sites 6–9), bulk density was lower in the subsoil (mean 0.21 g cm^{-3}) than in the topsoil (mean 0.36 g cm^{-3}) (Figure 5g). This difference is greater than reported by Harpenslager *et al*. (2015). There was no difference in organic matter content (loss on ignition) between topsoil and subsoil at Sites 6–9 (Figure 5d), while the opposite was found by Harpenslager *et al*. (2015).

CO_2 emissions and soil properties

Even though 12 of the 13 soils analysed were classified as Histosols, they exhibited a wide range in measured soil properties and CO_2 emissions. Soil 5 had the highest CO_2 emissions and the peaty marl (Soil 4) had the lowest. These two soils were collected a few kilometres apart in the same peatland belt. Site 5 is highly influenced by its $CaCO_3$ rich marl subsoil. However, abiotic production of CO_2 from $CaCO_3$ is considered negligible compared with biotic CO_2 emissions (Kuzyakov 2006). Moreover, Soils 6–8, all taken from the same farm, illustrate how peat soil properties and CO_2 emissions can differ within a relatively small area (< 1 km apart).

The linear relationship found between CO_2 emissions and NH_4 concentrations when Soil 7 was omitted (Figure 5f) suggests that the nutrient status of the soils influenced CO_2 emissions. This was also seen by Renou-Wilson *et al*. (2014), where a nutrient-rich drained peatland emitted more CO_2 than a parallel nutrient-poor drained peatland. Pohl *et al*. (2015) reported a strong relationship between nitrogen content and CO_2 flux from organic soils, although with wide variation in CO_2 emissions between different soils, as was also found in the present study. The subsoil at Site 9 had high $WEOC_{tot}$ and $WEOC_{fil}$ values, which could be the reason for the dark colour of drainage water from Soil 9 observed by Berglund & Berglund (2011). There was no clear relationship between $WEOC_{tot}/WEOC_{fil}$ and CO_2 emissions although the high $WEOC_{tot}/WEOC_{fil}$ values could potentially lead to high leaching losses to surrounding waters, with subsequent CO_2 emissions (Evans *et al*. 2016).

In this study the cultivated peat soils were of similar fen peat origin, probably because of the suitability of fen peat for agriculture. In a study by Moore & Dalva (1997), the botanical origin of the peat was the most important factor regulating CO_2 production, with herbaceous peat giving higher CO_2 production than peat originating from mosses or ligneous vegetation. The nutrient status of the original peat can also influence CO_2 production, with a eutrophic soil producing higher CO_2 emissions than a mesotrophic soil in a study by Aerts & Ludwig (1997).

The great variation in soil properties and CO_2 emissions between soils, and the great spatial variation within short distances, must be taken into account when deciding how to manage these soils in the future.

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REFERENCES

Aerts, R. & Ludwig, F. (1997) Water-table changes and nutritional status affect trace gas emissions from laboratory columns of peatland soils. *Soil Biology & Biochemistry*, 29, 1691–1698.

Berglund, K. (1989) *Ytsänkning på Mosstorvjord* (*Subsidence of Moss Peat Soil*). Technical Report Avdelningsmeddelande 89:3, Institutionen för markvetenskap, avdelningen för lantbrukets hydroteknik, Sveriges lantbruksuniversitet, Uppsala (in Swedish).

 DOI: 10.19189/MaP.2017.OMB.284

Berglund, Ö. & Berglund, K. (2010) Distribution and cultivation intensity of agricultural peat and gyttja soils in Sweden and estimation of greenhouse gas emissions from cultivated peat soils. *Geoderma*, 154, 173–180.

Berglund, Ö. & Berglund, K. (2011) Influence of water table level and soil properties on emissions of greenhouse gases from cultivated peat soil. *Soil Biology & Biochemistry*, 43, 923–931.

Berglund, Ö., Berglund, K. & Klemedtsson, L. (2010) A lysimeter study on the effect of temperature on CO_2 emission from cultivated peat soils. *Geoderma*, 154, 211–218.

Beyer, C., Liebersbach, H. & Höper, H. (2015) Multiyear greenhouse gas flux measurements on a temperate fen soil used for cropland or grassland. *Journal of Plant Nutrition and Soil Science*, 178, 99–111.

Biasi, C., Jokinen, S., Marushchak, M.E., Hamalainen, K., Trubnikova, T., Oinonen, M. & Martikainen, P.J. (2014) Microbial respiration in Arctic upland and peat soils as a source of atmospheric carbon dioxide. *Ecosystems*, 17, 112–126.

Bowen, S.R., Gregorich, E.G. & Hopkins, D.W. (2009) Biochemical properties and biodegradation of dissolved organic matter from soils. *Biology and Fertility of Soils*, 45, 733–742.

Campbell, D.I., Wall, A.M., Nieveen, J.P. & Schipper, L.A. (2015) Variations in CO_2 exchange for dairy farms with year-round rotational grazing on drained peatlands. *Agriculture, Ecosystems & Environment*, 202, 68–78.

Carrera, N., van Bodegom, P.M., van Hal, J.R., Logtestijn, R., Barreal, M.E. & Briones, M.J.I. (2015) Disentangling thermal acclimation and substrate limitation effects on C and N cycling in peatlands. *Soil Biology & Biochemistry*, 90, 224–231.

Chow, A.T., Tanji, K.K., Gao, S. & Dahlgren, F.A. (2006) Temperature, water content and wet-dry cycle effects on DOC production and carbon mineralization in agricultural peat soils. *Soil Biology and Biochemistry*, 38, 477–488.

Danevčič, T., Mandic-Mulec, I., Stres, B., Stopar, D. & Hacin, J. (2010) Emissions of CO_2, CH_4 and N_2O from Southern European peatlands. *Soil Biology & Biochemistry*, 42, 1437–1446.

Eickenscheidt, T., Heinichen, J. & Drösler, M. (2015) The greenhouse gas balance of a drained fen peatland is mainly controlled by land-use rather than soil organic carbon content. *Biogeosciences*, 12, 5161–5184.

Evans, C.D., Renou-Wilson, F. & Strack, M. (2016) The role of waterborne carbon in the greenhouse gas balance of drained and re-wetted peatlands. *Aquatic Sciences*, 78, 573–590.

Ghani, A., Dexter, M. & Perrott, K.W. (2003) Hot-water extractable carbon in soils: a sensitive measurement for determining impacts of fertilisation, grazing and cultivation. *Soil Biology & Biochemistry*, 35, 1231–1243.

Glatzel, S., Basiliko, N. & Moore, T. (2004) Carbon dioxide and methane production potentials of peats from natural, harvested, and restored sites, eastern Quebec, Canada. *Wetlands*, 24, 261–267.

Haddaway, N.R., Burden, A., Evans, C.D., Healey, J.R., Jones, D.L., Dalrymple, S.E. & Pullin, A.S. (2014) Evaluating effects of land management on greenhouse gas fluxes and carbon balances in boreo-temperate lowland peatland systems. *Environmental Evidence*, 3(5), 1–30.

Harpenslager, S.F., van den Elzen, E., Kox, M.A.R., Smolders, A.J.P., Ettwig, K.F. & Lamers, L.P.M. (2015) Rewetting former agricultural peatlands: Topsoil removal as a prerequisite to avoid strong nutrient and greenhouse gas emissions. *Ecological Engineering*, 84, 159–168.

Hjerpe, K., Eriksson, H., Kanth, M., Boström, B., Berglund, K., Berglund, Ö., Lundblad, M., Kasimir, Å., Klemedtsson, L., Eksvärd, J., Lindgren, A. & Svensson, E. (2014) *Utsläpp av Växthusgaser från Torvmark* (*Emissions of Greenhouse Gases from Peat Soils*). Report RA14:24, Jordbruksverket, Jönköping, 68 pp. (in Swedish).

Joosten, H. (2009) T*he Global Peatland CO_2 Picture: Peatland Status and Drainage Related Emissions in all Countries of the World*. Wetlands International, Wageningen, Netherlands, 35 pp.

Kainiemi, V., Arvidsson, J. & Kätterer, T. (2015) Effects of autumn tillage and residue management on soil respiration in a long-term field experiment in Sweden. *Journal of Plant Nutrition and Soil Science*, 178, 189–198.

Karki, S., Elsgaard, L., Audet, J. & Laerke, P.E. (2014) Mitigation of greenhouse gas emissions from reed canary grass in paludiculture: effect of groundwater level. *Plant and Soil*, 383, 217–230.

Kløve, B., Berglund, K., Berglund, Ö., Weldon, S. & Maljanen, M. (2017) Future options for cultivated Nordic peat soils: Can land management and rewetting control greenhouse gas emissions? *Environmental Science & Policy*, 69, 85–93.

Knox, S.H., Sturtevant, C., Matthes, J.H., Koteen, L., Verfaillie, J. & Baldocchi, D. (2015) Agricultural peatland restoration: effects of land-use change on greenhouse gas (CO_2 and CH_4) fluxes in the Sacramento-San Joaquin Delta. *Global Change*

 DOI: 10.19189/MaP.2017.OMB.284

Biology, 21, 750–765.

Kuzyakov, Y. (2006) Sources of CO_2 efflux from soil and review of partitioning methods. *Soil Biology & Biochemistry*, 38, 425–448.

Mäkiranta, P., Laiho, R., Fritze, H., Hytönen, J., Laine, J. & Minkkinen, K. (2009) Indirect regulation of heterotrophic peat soil respiration by water level via microbial community structure and temperature sensitivity. *Soil Biology & Biochemistry*, 41, 695–703.

Moore, T.R. & Dalva, M. (1993) The influence of temperature and water-table position on carbon-dioxide and methane emissions from laboratory columns of peatland soils. *Journal of Soil Science*, 44, 651–664.

Moore, T.R. & Dalva, M. (1997) Methane and carbon dioxide exchange potentials of peat soils in aerobic and anaerobic laboratory incubations. *Soil Biology & Biochemistry*, 29, 1157–1164.

Mustamo, P., Hyvarinen, M., Ronkanen, A.K. & Kløve, B. (2016) Physical properties of peat soils under different land use options. *Soil Use and Management*, 32, 400–410.

Norberg, L., Berglund, Ö. & Berglund, K. (2016a) Seasonal CO_2 emission under different cropping systems on Histosols in southern Sweden. *Geoderma Regional*, 7, 338–345.

Norberg, L., Berglund, Ö. & Berglund, K. (2016b) Nitrous oxide and methane fluxes during the growing season from cultivated peat soils, peaty marl and gyttja clay under different cropping systems. *Acta Agriculturae Scandinavica, Section B — Soil & Plant Science*, 66, 602–612.

Pahkakangas, S., Berglund, Ö., Lundblad, M. & Karltun, E. (2016) *Land Use on Organic Soils in Sweden - a Survey on the Land Use of Organic Soils Within Agriculture and Forest Lands During 1983–2014*. Report 21, Department of Soil and Environment, Uppsala, 37 pp.

Pohl, M., Hoffmann, M., Hagemann, U., Giebels, M., Borraz, E.A., Sommer, M. & Augustin, J. (2015) Dynamic C and N stocks - key factors controlling the C gas exchange of maize in heterogenous peatland. *Biogeosciences*, 12, 2737–2752.

Poyda, A., Reinsch, T., Kluβ, C., Loges, R. & Taube, F. (2016) Greenhouse gas emissions from fen soils used for forage production in northern Germany. *Biogeosciences*, 13, 5221–5244.

Price, J. (1997) Soil moisture, water tension, and water table relationships in a managed cutover bog. *Journal of Hydrology*, 202, 21–32.

Regina, K., Sheehy, J. & Myllys, M. (2015) Mitigating greenhouse gas fluxes from cultivated organic soils with raised water table. *Mitigation and Adaptation Strategies for Global Change*, 20, 1529–1544.

Renger, M., Wessolek, G., Schwarzel, K., Sauerbrey, R. & Siewert, C. (2002) Aspects of peat conservation and water management. *Journal of Plant Nutrition and Soil Science-Zeitschrift Fur Pflanzenernahrung Und Bodenkunde*, 165, 487–493.

Renou-Wilson, F., Barry, C., Muller, C. & Wilson, D. (2014) The impacts of drainage, nutrient status and management practice on the full carbon balance of grasslands on organic soils in a maritime temperate zone. *Biogeosciences*, 11, 4361–4379.

Renou-Wilson, F., Müller, C., Moser, G. & Wilson, D. (2016) To graze or not to graze? Four years greenhouse gas balances and vegetation composition from a drained and a rewetted organic soil under grassland. *Agriculture, Ecosystems and Environment*, 222, 156–170.

Romano, N., Hopmans, J.W. & Dane, J.H. (2002) Suction Table. In: Dane, J.H. & Topp, C.G. (eds.) *Methods of Soil Analysis, Part 4 - Physical Methods*. Soil Science Society of America, Madison, Wisconsin, USA, 692–698.

Scanlon, D. & Moore, T.R. (2000) Carbon dioxide production from peatland soil profiles: The influence of temperature, oxic/anoxic conditions and substrate. *Journal of Soil Science*, 165, 153–160.

Schrier-Uijl, A.P., Kroon, P.S., Hendriks, D.M.D., Hensen, A., Van Huissteden, J., Berendse, F. & Veenendaal, E.M. (2014) Agricultural peatlands: towards a greenhouse gas sink - a synthesis of a Dutch landscape study. *Biogeosciences*, 11, 4559–4576.

Soil Survey Staff (2014) *Keys to Soil Taxonomy, Twelfth Edition*. Natural Resources Conservation Service, United States Department of Agriculture (USDA), Washington DC, 372 pp. Online at: https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/class/taxonomy/?cid=nrcs142p2_053580, accessed 02 Mar 2018.

Susilawati, H.L., Setyanto, P., Ariani, M., Hervani, A. & Inubushi, K. (2016) Influence of water depth and soil amelioration on greenhouse gas emissions from peat soil columns. *Soil Science and Plant Nutrition*, 62, 57–68.

Szafranek-Nakonieczna, A. & Stepniewska, Z. (2014) Aerobic and anaerobic respiration in profiles of Polesie Lubelskie peatlands. *International Agrophysics*, 28, 219–229.

Tiemeyer, B., Albiac Borraz, E., Augustin, J., Bechtold, M., Beetz, S., Beyer, C., Drösler, M., Ebli, M., Eickenscheidt, T., Fiedler, S., Förster, C., Freibauer, A., Giebels, M., Glatzel, S.,

 DOI: 10.19189/MaP.2017.OMB.284

Heinichen, J., Hoffmann, M., Höper, H., Jurasinski, G., Leiber-Sauheitl, K., Peichl-Brak, M., Roßkopf, N., Sommer, M. & Zeitz, J. (2016) High emissions of greenhouse gases from grasslands on peat and other organic soils. *Global Change Biology*, 22, 4134–4149.

von Post, L. (1922) Sveriges Geologiska Undersöknings torvinventering och några av dess hittills vunna resultat (Geological Survey of Sweden's peat inventory and some of its achievements so far). *Svenska Mosskultur-föreningens tidskrift*, 36, 1–27 (in Swedish).

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